# KNOWLEDGE IS POWER

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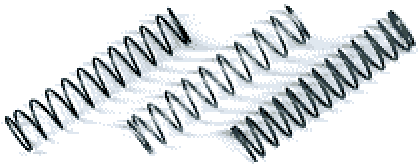
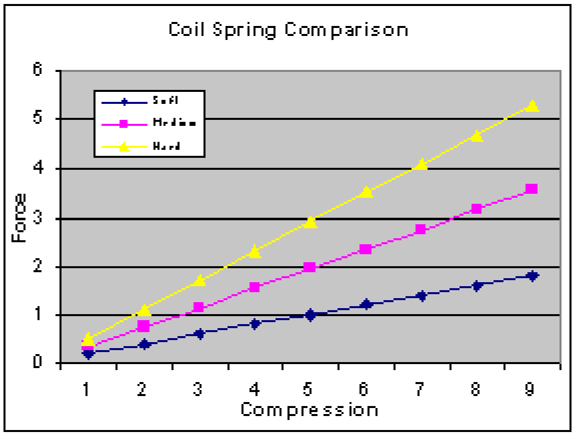
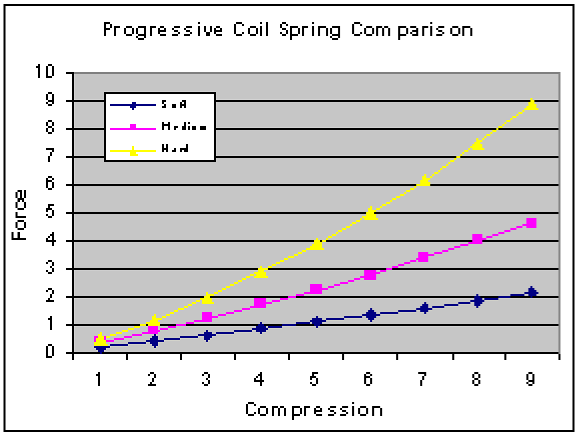
# 1. SUSPENSION COMPONENTS

## *1.1. Springs*

The most common variety of springs are coil springs (see picture), these are usually placed around the damper housing to form a spring-damper unit. A spring is an elastic device that resists movement in its direction of work. The force it exerts is proportional to the movement of one of its ends. Or to put this into a mathematical equation: Force = movement * spring constant. A high value for the spring constant makes for a stiff spring, and a low value makes for a soft spring.







For progressive springs the spring constant will increase as the spring goes deeper into its travel, and for regressive springs it will decrease with travel. Most coil springs are slightly progressive, because as they compress, some of the coils start touching each other, especially near the top and the bottom, and hence the number of active coils decreases.

So math wise, springs aren’t very complicated, but handling wise, they are. The problem is that they work in two dimensions: left to right and front to rear. For example: a car with soft springs will experience a lot of body roll in fast turns, but it will also dive very hard under heavy breaking and squat a lot while accelerating. This is because the springs have to absorb the torque’s that are generated (see roll centre and anti-squat), and soft springs need to be compressed over a larger distance to be able to absorb a certain force. (If this doesn't make sense, I suggest you take another good look at the graph) Note that both observations have the same effect: more load on the front tires. So you might think: "Why make a big deal out of this, the effect is the same." It's a big deal because by the time you have read all of the chapters, you'll be able to adjust a car's lateral balance independent from its longitudinal balance, but for now, just remember that spring stiffness affects just about anything: bump handling, roll stiffness, pitch stiffness….

In general, you could say that stiffer springs yield less grip, and conversely, softer springs yield more grip. This is because springs inhibit weight transfer, both front-to-rear and left-to-right: for the same cornering, acceleration or braking force a stiffer spring will compress less, resulting in less chassis movement and thus also less weight transfer, and a soft spring will compress a lot, resulting in a lot of weight transfer.

But, you won’t always be able to use the spring you want: on small, high frequency bumps, stiff springs will make the car bounce, resulting in a loss of grip. So you need softer springs, because they allow the tires to stay in contact with the ground. On smooth tracks however, stiff springs are the way to go, they will also help the car’s jumping ability and responsiveness.

## 1.2. Damping

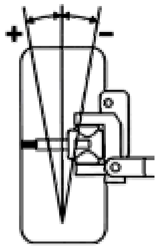
Damping is needed to absorb the energy associated with suspension travel. Bumps or lateral or longitudinal acceleration can induce that suspension travel. Without damping, the magnitude of the suspension movement would never stop increasing, leading to a very humorous situation. In terms of energy, damping **absorbs** most of the energy the car receives as it moves, unlike springs, which **store** the energy, and release it again. Imagine a car with no damping driving on a bumpy road. The subsequent impacts from the bumps on the tires would make the suspension bounce very intensely, which is not a good thing. Dampers absorb all the excess energy, and allow the tires to stay in contact with the ground as much as possible. This also indicates that the damping should always be matched to the spring ratio: never run a very stiff spring with very soft damping or a very soft spring with very stiff damping. Small changes however can give interesting results. Damping that’s a bit on the heavy side will make the car more stable; it will slow down both the vehicle’s pitch and roll motions, making it feel less twitchy. Note that damping only alters the **speed** at which the rolling and pitching motions occur, it does not alter their extent. So if you want your vehicle to roll less, adjust the anti-roll bars, or the springs, but not the dampers.

Something you can adjust with the damping rate is the speed at which the suspension rebounds: if a car with soft springs but hard dampers is pushed down, it will rebound very slowly, and a car with stiff springs and light damping will rebound very quickly. The same situation occurs when exiting corners: in the corner, the weight is transferred, and the chassis has rolled and/or dived, but when the steering is straightened out, and the cornering force disappears, the chassis comes back to its original position. The speed at which this happens is controlled by the damping rate. So the car with the soft springs and hard damping will tend to want to continue turning when the steering is straightened. It will also tend to continue running straight when steering is first applied; it will feel generally unresponsive, yet very smooth. The car with firm springs and soft damping will be very responsive: it will follow the driver’s commands very quickly and aggressively.

You may not always be able to use the spring and damping rates you’d like, because of bumps. Small, high-frequency bumps require soft settings for both damping and springs. You can’t use such soft settings for big, harsh bumps, because the car would bottom out a lot, so you’ll need to set your car a little stiffer. On very smooth tracks you can use very stiff settings for both springs and damping.

But it’s not quite as simple as that: even in the simple dampers used in R/C cars, there is a difference between high-speed and low-speed damping. They’re also independently adjustable.

## 1.3. Camber

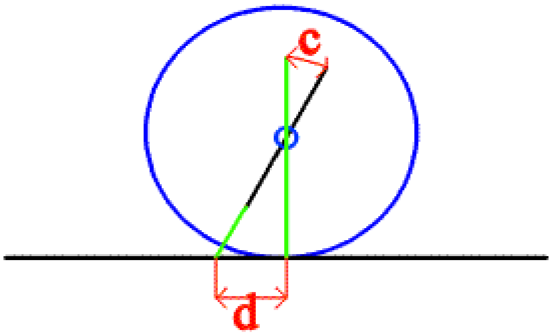


Camber describes the angle between the tyre’s centreline and the vertical plane. If the wheels of the car lean inwards, the camber angle is said to be negative, if they lean outward, the angle is said to be positive. It is usually measured at ride height, and angles of -0.5 to -3 are the most common.

First of all, positive camber is never used, only negative. Negative camber is necessary because when a car turn into a corner, it experiences chassis roll, which increases the tires' camber angle. Also, because most rubber tires are quite flexible, they get a little deformed in the direction of the centre of the corner. If the car doesn't have any negative camber, only the tires' outer edge and sidewall would touch the ground, which isn't beneficial for traction. A tyre’s coefficient of traction (grip) increases as it's contact surface increases, so the ideal situation would be that the tire would stay perpendicular to the ground at all times, and that it wouldn't deform under heavy side load. Unfortunately, this isn't the case; most of the time you have to find the best compromise. The problem is that if you want maximum forward traction, you have to set the camber to 0°, and if you want maximum cornering action you have to set it to a few degrees negative, depending on the softness of the suspension and tire carcass. So you can't have both, but you can try to make the best possible compromise. The easiest way is to set camber so the tires wear evenly across their surface, that way you can be sure every part of the surface is used to the maximum of it's potential. Keep in mind that a car with very soft suspension settings and very little camber change will need more negative camber than a car with a very stiff suspension and In very bumpy off-road conditions however, it can be beneficial to use more camber than would be needed for uniform wear across the surface. The excess camber stabilises the car in large bumps and reduces the risk of catching a rut and flipping over.

Camber can also be used as an adjustment to attain a desired handling effect, but I definitely don't recommend this: a non-optimal camber setting always yields less traction, which inevitably makes the car slow.

## 1.4. Caster



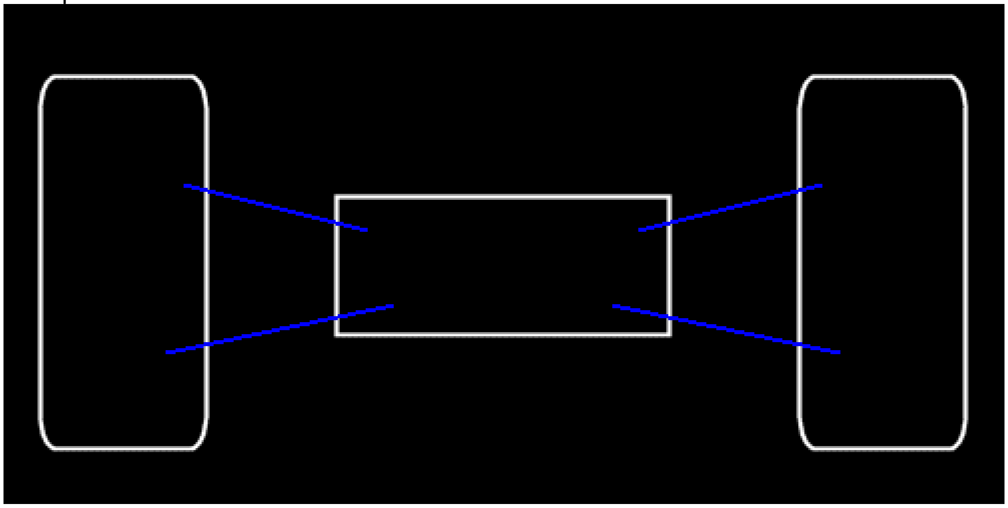
Caster describes the angle c between the kingpin and the vertical plane. In case of a double wishbone-type of suspension, the axis through the centres of the ball links serves as a 'virtual hinge pin'. If the kingpin is leaning back, as in the picture, the caster angle is said to be positive. Negative caster (kingpin leaning towards the front) is never used. Note that the contact patch between the tire and the ground is behind the intersection point of the extension of the kingpin and the earth. (Dimension d) This will cause the wheels to 'trail'.

The caster angle will cause excessive camber in the front wheels as they are steered, lifting the front of the car up. This lifting effect is what causes the front wheels to have a tendency to straighten out when there's no steering force applied: when the wheels are pointed straight ahead, the chassis sits at its lowest position, steering the wheels requires some force, to lift the car up. When the force is removed, gravity will return the wheel to their original position. The bigger the caster angle, and the heavier the car, the stronger this effect is. Also, the bigger he caster angle, the bigger the camber difference induced when the wheels are steered. This camber difference is to compensate for the chassis roll and tire squirm when the car is cornering. Hence, a lot of caster will provide more steering in high-speed corners, where chassis roll is more pronounced, and whilst turning in. It will also make the car more stable in rough conditions, and the car's straight-line stability will also be improved. A small caster angle will provide more steering in low-speed corners and less turn-in.

## 1.5. Roll Centre

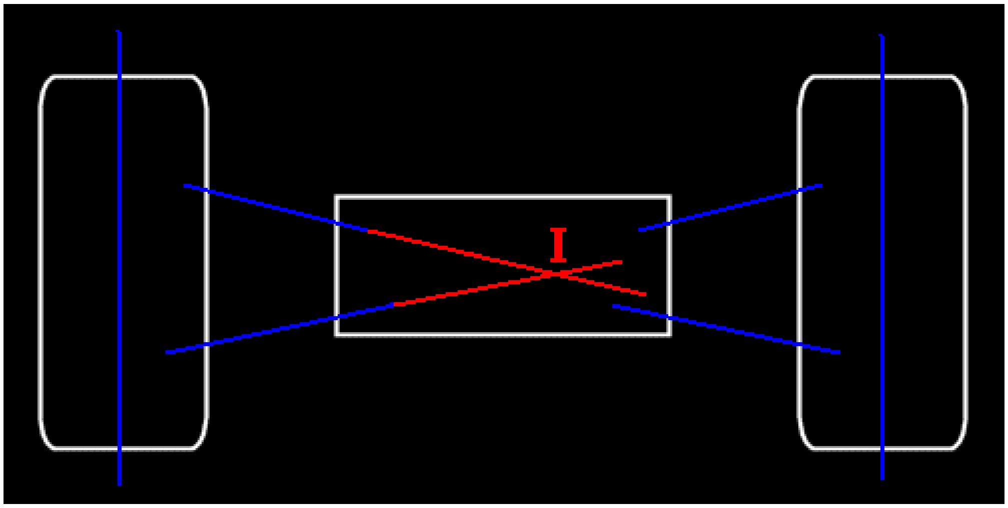
Predicting how a car will react when forces are applied at the tires is not easy. The force can be absorbed, split, converted into a torque... by all sorts of suspension components. To avoid all of this you can try to find the roll centre of your car and try to predict the reaction of the car from there. A roll centre is an imaginary point in space, look at it as the virtual hinge your car hinges around when its chassis rolls in a corner. It's as if the suspension components force the chassis to pivot around this point in space.

Let's look at the theory behind it first. The theorem of Kennedy tells us that if three objects are hinged together, there are at most three poles of movement, and they are always collinear, i.e. they are always on one line. To understand what a pole really is, consider the analogy with the poles of the earth: as earth rotates, the poles stay where they are. In other words, the earth rotates around the imaginary axis that connects the two poles. Now this is a 3-dimensional analogy, in the case of the roll centre we only need two dimensions at first. So a pole of an object (or a group of objects) is like the centre point of a circle it describes.



If we look at the suspension of a typical R/C car, with a lower A-arm and an upper link, we see a bunch of objects that are all hinged together. These objects include the chassis, the upper link, the A-arm, and the hub. For now we consider the hub, the axle and the wheel as one unit. First, let's look at the chassis, the upper link and the hub. They are hinged together, so the theorem of Kennedy applies. The pole of the upper link and the hub is the ball joint that connects them, because they both hinge around it. The pole of the upper link and the chassis is also the ball joint that connects them. So if we now look at the chassis, the upper link and the hub, we have already found two of the three poles, so if there is a third one, it should be on the imaginary line that connects the other two. That line is drawn in red on the next drawing.

The same applies to the bottom half of the suspension system, the pole of the lower A-arm and the hub is the outer hinge pin, the pole of the A-arm and the chassis is the inner hinge pin, so if there is a third pole it should be on the line that connects the other two. That line is also drawn in red. If your car uses ball links instead of hinge pins, the axis through the centres of the two balls makes up a virtual hinge pin.



If the two red lines intersect, the pole of the hub/wheel and the chassis is the intersection point I.

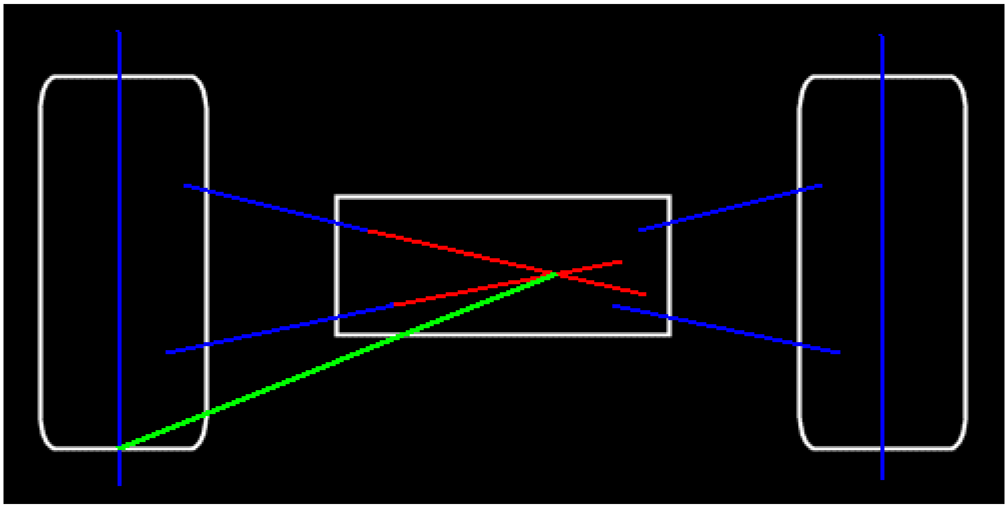
The distance from point I to the centreline of the tire is sometimes referred to as 'swing axle length', it's as if the hub/wheel is attached to an imaginary swing axle which hinges around point I. Having that long swing axle would be equivalent to having the double wishbone-type suspension, but the actual construction would be very impractical. Nevertheless it serves as a good simplification. The swing axle length, together with the angle, determine the amount of camber change the wheel will experience during the compression of the suspension. A long swing axle length will cause very little camber change as the suspension is compressed, and a very short one will cause a lot.

If the upper link and the A-arm are perfectly parallel to each other, the two red lines won't intersect, or, in other words, the intersection point I is infinitely far removed from the car. This isn't a problem though: just draw the green line (in the next drawing) parallel to the two red ones.

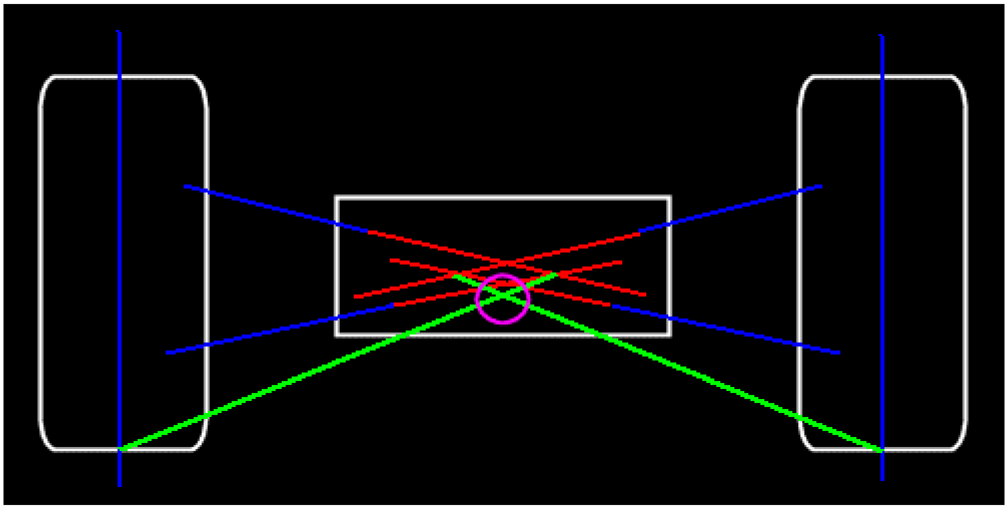
The two red lines should always intersect on the side of the centre of the car, if they intersect on the outside, camber change will be bizarre: it will go from negative to positive back to negative, which is not a good thing for the consistency of the traction.

The wheel and the ground can also move relative to each other; let's assume the wheel can pivot around the point where it touches the ground, which is usually in the middle of the tire carcass. That point is the pole of the tire and the ground. As it is drawn, a problem might arise when the chassis rolls: the tires might also roll, and hence the contact point between the earth and the tire might shift, especially with square-carcass tires that don't flex much.

Now we can apply the theorem of Kennedy again: the ground, the wheel and the chassis are hinged together, we have already found the pole of the wheel and the ground, and the pole of the wheel and the chassis. If the pole of the ground and the chassis exists, it should be somewhere on the line that connects the other two poles, drawn in green in the next drawing.



The same procedure can be followed for the other half of the suspension, as in the picture below. Again a green line will be found the pole of the ground and the chassis should be on. The intersection point of the two green lines is the pole of the ground and the chassis. (Circled in purple)



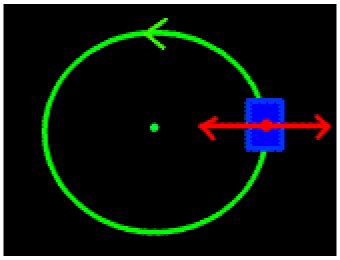
That point (purple), the pole of the chassis and the ground is also called the **roll centre** of the chassis. Theoretically, the ground could rotate around it while the chassis would sit still, but usually it's the other way around; the chassis rotates around it while the ground sits still.

The roll centre is also the only point in space where a force could be applied to the chassis that wouldn't make it roll.

The roll centre will move when the suspension is compressed or lifted, that's why it's actually an **instantaneous** roll centre. It moves because the suspension components don't move in perfect circles relative to each other, most of the paths of motion are more random. Luckily every path can be described as an infinite series of infinitely small circle segments. So it doesn't really matter the chassis doesn't roll in a perfect circular motion, just look at it as rolling in a circle around a centre point that moves around all the time.

If you want to determine the location of the roll centre of your car, you can either 'eyeball' it by imagining the lines and intersection points, or you can get a really big sheet of paper and make a scale drawing of your car's suspension system.

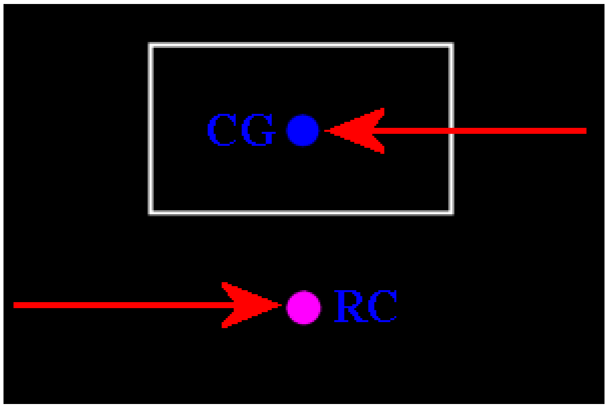
Now that we know where the roll centre (RC) is located, let's look at how it influences the handling of the car. Imagine a car, driving in a circle with a constant radius, at a constant speed. An inertial force is pulling the car away from the centre point, but because the car is dynamically balanced, there should be a force equal but opposite, pulling the car towards the centre point. This force is provided by the adhesion of the tires.



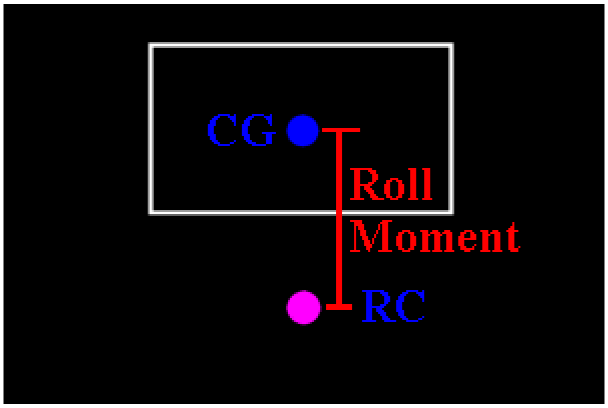
In principle, the inertia force works on all the different masses of the car, in every point, but by determining the centre of gravity (CG) it's possible to replace all of the inertia forces by one big force working in the CG. It's as if the total mass of the car is packed into one point in space, the CG. If the CG is determined correctly, both conditions should be perfectly equivalent.

The forces generated by the tires can be combined to one force, working in the car's roll centre.

Viewed from the back of the car, it looks like this:



Two equal, but opposite forces, not working in the same point generate a torque equal to the size of the two forces multiplied by the distance between them. So the bigger that distance, the more efficiently a given pair of forces can generate a torque onto the chassis. That distance is called **the roll moment**. Note that it is always the **vertical** distance between the CG and the RC, since the forces always work horizontally.

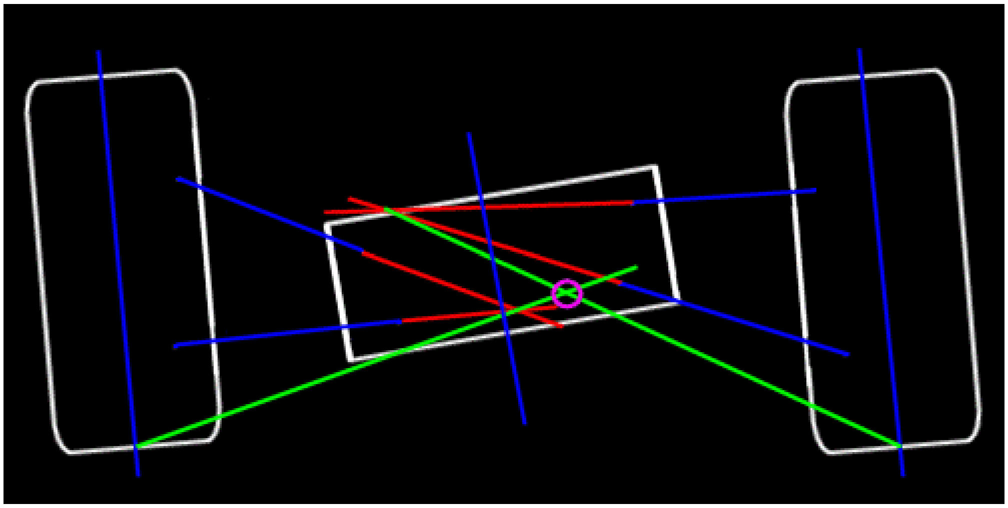


The torque generated by the two forces will make the chassis roll, around the roll centre. This rolling motion will continue until the torque generated by the springs is equally big, only opposite. The dampers determine the speed at which this happens. Note that the roll torque is constant, well at least in this example where the turning radius is constant, but the torque supplied by the springs increases as the suspension is compressed. (See chapter 'springs') The difference between the two torque's, the resultant, is what makes the chassis lean. This resultant decreases because the torque supplied by the spring's increases. So the speed at which chassis roll takes place always decreases, and it reaches zero when both torques are equal. So for a given spring stiffness a big roll moment will make the chassis roll very far in the corners, and a small roll moment will make the chassis lean over less. This also explains why a vehicle with a high CG has a tendency to lean very far in a corner, and possibly tip over.

So at any given time, the size of the roll moment is an indication of the size of the torque that causes the chassis to lean over while cornering.

Now; a different problem arises; the location of the roll centre changes when the suspension is compressed or extended, most of the time it moves in the same direction as the chassis, so if the suspension is compressed, the RC drops.

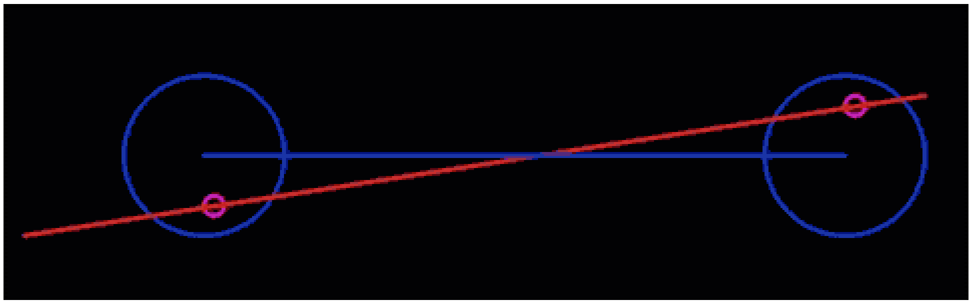
When the car corners, and the chassis leans over, the RC usually moves away from the chassis' centreline.



Most R/C cars allow for the length and position of the upper link to be changed, and thus change the roll characteristics of the car. The following generalisations apply in most cases. An upper link that is parallel to the lower A-arm will make the RC sit very low when the car is at normal ride height, hence the initial body roll when entering a corner will be big. An upper link that is angled down will make the RC sit up higher, making the initial roll moment smaller, which makes that particular end of the car feel very aggressive entering the corner. A very long upper link will make that the roll moment stays more or less the same size when the chassis leans over; that end of the chassis will roll very deeply into the suspension travel. If not a lot of camber is used, this can make the tires slide because of excessive positive camber. A short upper link will make that the roll moment becomes a lot smaller when the chassis leans; the chassis won't roll very far.

Until now, we've ignored the fact that there are two independent suspension systems in a car; there's one in the front and one in the rear. They both have their own roll centre. Because the 'chassis' parts of both systems are connected by a rigid structure, the chassis, they will influence each other. Some people tend to forget this when they're making adjustments to their cars; they start adjusting one end without even considering what the other end is doing. Needless to say this can lead to anomalies in the car's handling. Having a very flexible chassis can hide those anomalies somewhat, but it's a far cry from a real solution.

Anyway, the front part of the chassis is forced to hinge on the front RC, and the rear part is forced to hinge on the rear RC. If the chassis is rigid, it will be forced to hinge on the axis that connects both RC's (purple), that axis is called **the roll axis**. (red)



The position of the roll axis relative to the cars CG tells a lot about the cornering power of the car; it predicts how the car will react when taking a turn. If the roll axis is angled down towards the front, the front will roll deeper into its suspension travel than the rear, giving the car a ’nose down’ attitude in the corner. Because the rear roll moment is small relative to the front, the rear won’t roll very far; hence the chassis will stay close to ride height. Note that with a car with very little negative suspension travel (droop) the chassis will drop more efficiently when the car leans over. With the nose of the car low and the back up high, a bigger percentage of the cars weight will be supported by the front tires, more tire pressure means more grip, so the car will have a lot of grip in the front, making it oversteer. A roll axis that is angled down towards the rear will promote understeer. Remember that the position of the roll centres is a dynamic condition, so the roll axis can actually tilt when the car goes through bumps or takes a corner, so it’s possible for a car to understeer when entering the corner, when chassis roll is less pronounced, and oversteer in the middle of the corner because the front RC has dropped down a lot. This example illustrates how roll centre characteristics can be used to tune a car to meet specific handling requests, from either the driver or the track.

In general, you could say that the angle of the upper link relative to the A-arm determines where the roll centre is with the chassis in its neutral position, and that the length of the upper link determines how much the height of the RC changes as the chassis rolls. A long, parallel link will locate the RC very low, and it will stay very low as the car corners. Hence, the car (well at least that end of the car) will roll a lot. An upper link that’s angled down and very short will locate the RC very high and it will stay high as the chassis rolls. So the chassis will roll very little. Alternatively, a short, parallel link will make the car roll a lot at first, but as it rolls, the tendency will diminish. So it will roll very fast at first, but it will stop quickly. And a long link that’s angled down will reduce the car’s tendency to roll initially, but as the chassis rolls it won’t make much of a difference anymore.

In terms of car handling, this means that the end where the link is angled down the most (highest RC) has the most grip initially, when turning in, or exiting the corner, and that the end with the lowest RC when the chassis is rolled will have the most grip in the middle of the corner. So if you need a little more steering in the middle of the corners, lengthen the front upper link a little. (Be sure to adjust camber afterwards) If you’d like more aggressive turn-in, and more low-speed steering, either set the rear upper link at less of an angle, or increase the front link’s angle a little.

Now you might ask yourself: what’s the best, a high RC or a low one? It all depends on the rest of the car and the track. One thing is for sure: on a bumpy track, the RC is better placed a little higher; it will prevent the car from rolling from side to side a lot as it takes the bumps, and it will also make it possible to use softer springs which allow the tires to stay in contact with the bumpy soil. On smooth tracks, you can use a very low RC, combined with stiff springs, to increase the car’s responsiveness and jumping ability. More about this in chapter 6.

## 1.6. Anti-squat

Anti-squat describes the angle of the rear hinge-pins relative to the horizontal plane. Its purpose is to make the car squat less when accelerating. (Squatting is when the rear of the car drops down when the car accelerates)

More anti-squat will give more ’driving traction’: there will be more pressure on the rear tires as you accelerate, especially the first few meters. At the same time, it will give more on-power steering, because the car isn’t squatting much. The disadvantage is that the car has an increased tendency to become unstable entering corners, especially in the rear. Reducing the anti-squat angle has the opposite effect: a lot less on power steering, and more rear traction when the car isn’t accelerating as much anymore. The car will also be a lot more stable entering corners. It also affects the car’s ability to handle bumps: more anti-squat will cause the car to bounce more when accelerating through bumps, but it will increase the car’s ability to absorb the bumps when coasting. Reducing the anti-squat does the opposite: it improves the car’s ability to soak up the bumps under power, but reduces it while coasting.

## 1.7. Ride Height

Proper ride height is very important, too low and the vehicle will bottom out a lot, too high and the risk of traction rolling will be unnecessarily big. Equal ride height front and rear is a good starting point. Raising or lowering ride height on one end of the car changes the steering characteristics of the car; the lowest end will have a slightly bigger percentage of the cars static weight. But, more importantly, the roll centre will also be lowered, making that particular end of the car roll deeper when the car corners, making it sit even lower and thus having more grip.

You should also be aware that changes in ride height usually influence the amount of down-travel too, which, as explained in the next section, can have serious consequences.

## 1.8. Suspension Travel

The amount of negative suspension travel (downtravel) a car has can have a huge effect on its handling; it influences both the mount of roll and the amount of pitch the chassis will experience.

With a lot of downtravel, as the chassis rolls into a turn, the height of the CG doesn’t change very much.

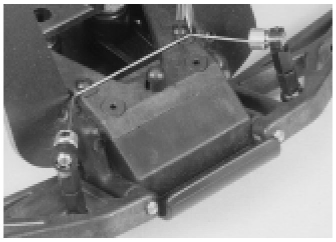
With almost no downtravel, as it rolls into a turn, the chassis is pulled down as it rolls, effectively lowering the CG.

So, if one end of the car has less downtravel than the other, that end will be forced down more in a turn, which makes for more grip at that end, especially in the middle part of the turn, where weight transfer is more pronounced. Very little downtravel at the front will give a lot of steering, especially when entering a corner at high speed, or very violently. Very little downtravel at the rear will give a lot, and consistent traction throughout the turn.

But that isn’t all there is to it: the amount of suspension travel also influences the car’s longitudinal balance, i.e. when braking and accelerating. An end with a lot of downtravel will be able to rise a lot, so chassis pitch will be more pronounced, which in turn will provide more weight transfer. For example: if the front end has a lot of downtravel, it will rise a lot during hard acceleration, transferring a lot of weight onto the rear axle. So the car will have very little on-power steering, but a lot of rear traction. A lot of downtravel at both ends, combined with soft springs, can lead to excessive weight transfer: on-power understeer, and off-power oversteer. The cure is simple: either reduce downtravel, or use stiffer springs.

There are also some disadvantages of having very little suspension travel: the bump handling and the car’s jumping ability may suffer, it will bottom out very easily.

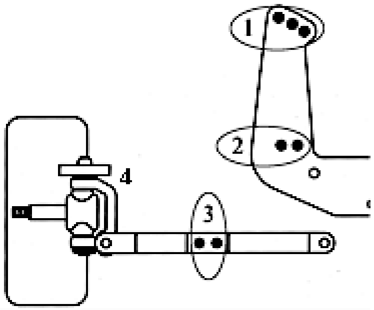
## 1.9. Anti-roll Bars



Anti-roll bars are like ’sideways springs’, they only work laterally. Here’s how they work: if one side of the suspension is compressed, one end of the bar is lifted. The other end will also go up, pulling the other side of the suspension up also, basically giving more resistance to chassis roll. How far and how strongly the other side will be pulled up depends on the stiffness and the thickness of the bar used: a thin bar will flex a lot, so it won’t pull the other side up very far, letting the chassis roll deeply into its suspension travel. Note that the bar only works when one side of the suspension is extended further than the other, like when the car is cornering. When both sides are equally far compressed, like when the car is braking, the bar has no effect. So anti-roll bars only affect the lateral balance of the car, not the longitudinal balance.

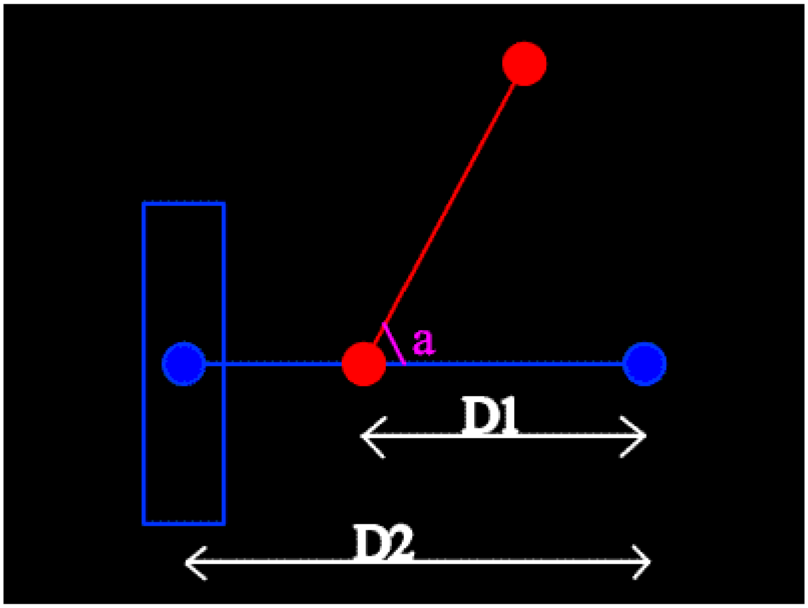
Unfortunately, anti-roll bars aren't the only things affecting the car's roll stiffness; they work in conjunction with the springs and dampers. Suppose you add an anti-roll bar at the rear of your car without changing any of the other settings. When the car enters a turn, the chassis starts to roll. Normally, the suspension on the outside of the turn would compress, and the one on the inside would extend, making for a lot more pressure on the outside tire. With the anti-roll bar however, the suspension on the inside will be compressed, so the chassis will roll less, and the rear of the car will sit lower than normal. So the rear has more weight on it, and it's distributed more evenly over the two tires. This makes for a little more and more consistent traction. Remember that this is in the beginning of the turn, the situation is different in the middle of the turn. Normally, without the anti-roll bar, the chassis would stop rolling when the roll torque is fully absorbed by the outside spring. But with the anti-roll bar, some of that torque is absorbed by the anti-roll bar, and used to compress the inside suspension. So the outside suspension won't be compressed as much as it normally would, making the rear of the chassis sit up higher than normal, so less weight is on the rear of the car, and more at on the front. It's as if suddenly the rear has become stiffer, making for more steering and a little less rear traction. Rear traction is more consistent however, because the weight is distributed more evenly over the rear tires, unless the track is really bumpy, that is; anti-roll bars can really mess up a car's rough track handling, so they're rarely used on bumpy tracks. Adding an anti-roll bar at the front of the car has a similar, but opposite effect: it decreases steering, but makes it much smoother and more consistent.

## 1.10. Shock mounting locations



Most R/C vehicles have several possible mounting points for the shock absorbers, both at the upper mount (area 1) and at the A-arm (area 3). By mounting the shocks in a different position, spring action can be altered. The question is: how will this affect the handling, or the 'feel' of the car? To understand this, first you need to know about **wheel rates.**

A wheel rate is an equivalent spring rate at the wheel; it's the spring rate of a spring that would give the same stiffness as the current one, if it was to be attached right at the centreline of the wheel. After all, that's where the traction forces act: at the wheel.



A wheel rate is defined as motion ratio$^2$ * spring rate * sin(spring angle), and motion ratio is the distance between the lower shock mounting position and the inner hinge pin divided by the distance between the inner hingepin and the tyre’s centreline. The spring angle is the angle between the shock and the lower A-arm.

Or: wheel rate = spring rate * $(D1/D2)^2$ * sin a

This formula tell us two things:

1. The more the shocks are inclined, the softer the wheel rate.
2. The closer the bottoms of the shocks are mounted to the middle of the chassis, the softer the spring rate.

Note that if you change the lower shock mounting location, you change both the shock angle and the motion ratio, but it's usually the change in motion ratio that has the biggest effect. This also shows in the formula: the motion ratio is squared, and the spring angle isn’t. The amount of suspension travel also changes, which can also affect the car's handling.

The shock angle isn't constant either: it gets bigger as the suspension is compressed. This effect is more pronounced as the shocks are more laid down, so the more inclined the shocks are, the more progressive the wheel rate will be. So think of the top mounting positions as a means of fine-tuning spring and damper rates, and changing the progressiveness.

Keep in mind this isn't perfectly correct: if the centreline of the tire doesn't intersect with the outer hinge pin, a considerable part of the forces acting on the tire are transmitted to the chassis along the upper link. Nevertheless, it's a very good approximation.

Since the shocks' angle changes their progressiveness, it also influences the shaft speed: if the shock is laid down (progressive), shaft speed will increase as the shock is compressed, if it is close to vertical (linear), shaft speed won't vary a lot with suspension travel. Obviously, this affects high-speed damping too; it affects when the transition from low-speed to high-speed damping occurs. It will occur earlier when the shock is closer to vertical, because when it is inclined, it takes some time (and some positive suspension travel) for the shaft to 'speed up', and reach the same shaft speed. So inclining the shocks more has more or less the same effect as using a piston with slightly bigger holes, and mounting it more upright has the same effect as using a piston with slightly smaller holes.

I find that changing the lower mounting location of the shocks comes in handy sometimes when you want to change the amount of negative suspension travel, but you don't feel like altering the length of the shock, or when you need the springs to be just a little stiffer or softer. Changing the top mounting location is a very subtle adjustment, I like to change it after all of the other, more important adjustments have been made, and the car is handling more or less the way I want it to. It's especially helpful to alter the 'feel' of the steering entering corners. Now I don't know if this applies when the springs' action is very progressive, but the more the shocks are stood up (less inclined), the more direct their action will be entering the corner. For instance: if the front shocks are close to vertical, and the rears are somewhat laid down, the car will have a lot of turn-in steering; it will be very responsive. If the rears are close to vertical, and the fronts are more laid down, the car won't have a lot of turn-in, but it will have more steering in the middle of the turn; it will 'square'. In some cases, the rear might actually begin to slide. It works much in the same way as having stiff springs or heavy damping: if you have stiff springs, or heavy damping up front, the initial reaction when you enter a turn will be very strong. In the middle part of the corner the car will probably understeer, but it's the initial reaction that gives the car a 'responsive' character. Even roll centre works this way: a very high roll centre in the front will make the car turn in very aggressively, but understeer in the middle of the corner. It's nice if you like an aggressive car you can 'throw' into the corners, but I doubt it's the fastest way round the track. Conversely, if the rear roll centre is set very high, the car will turn in very gently, and possibly oversteer after that.

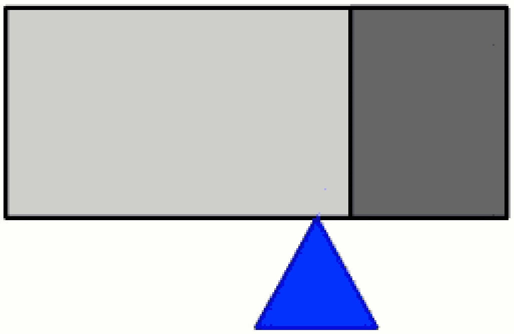
## 2. WEIGHT DISTRIBUTION

Weight distribution is very important; not only does it affect the static weight on the different tires, it also affects how the weight shifts in dynamic conditions.

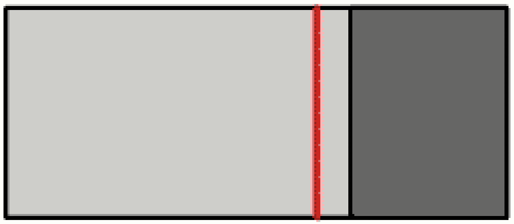
The easiest way to judge weight distribution is to determine the car's Centre of Gravity (CG). This is a point in space where the mass of the entire car is accounted for. Because of its location, it can be used to simplify the effects of inertia forces. In reality, every little bit of mass is subjected to inertia, but it's much easier to make use of an equivalent condition: assume all the mass of the object is concentrated in its centre point, i.e. it's CG. So instead of having to figure out how every part of a 1.5kg car reacts to a certain force, we only have to figure out how a weightless car with a 1.5kg dot in it's centre (the CG) reacts to it. The latter is much easier: the force only works in the CG, and not in the rest of the car.

Of course, this only works when the CG is determined correctly. I think that's a lot of work, and it might not be accurate, so I propose a different method. It's based on the fact that when an object is statically balanced, its CG is right above the point where it's supported. By applying this in three different planes, you can determine an object's CG. Here's an example.

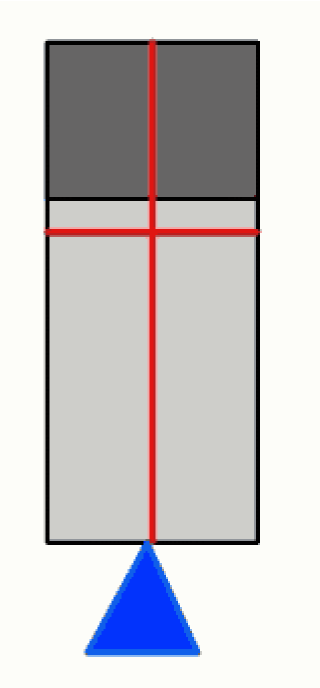
Here we have an object with a heavy part (dark) and a lighter part (bright) we'd like to determine the CG of. Since the right part is heavier the CG will probably be located somewhere at the right.



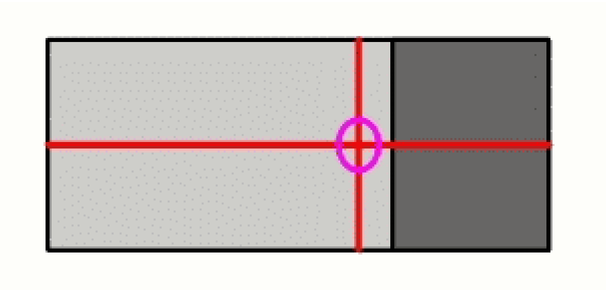
We try to balance it on a sharp edge, and this is the position in which the object stays put. So we know the CG is somewhere right above the point where the object is supported.



The red line contains all the points above the point where the object was being supported, so the CG has to be located somewhere on the red line.



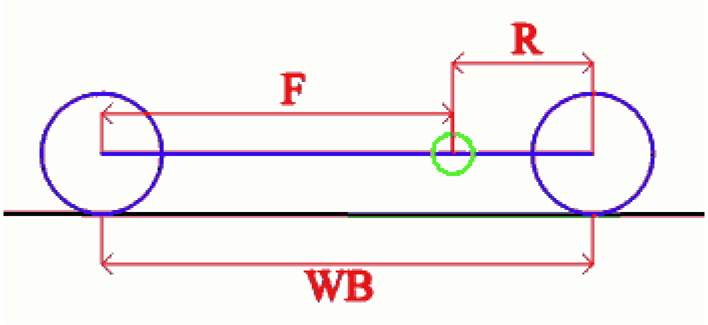
We can follow the same procedure, but in a different dimension. Again, we can draw a red line on which the CG is located.



Because this is a 2D example, trying to balance the object 2 times is sufficient to determine it's CG (circled in purple). For a car, which has 3 dimensions, you'll need to do it 3 times. It might impose some practical problems, but this is where you'll have to use your imagination.

Now that we know where the car's CG is located, we can easily calculate the amount of weight on the tires, and the weight distribution.

First, let's have a look at the front-to-rear weight distribution:



The wheelbase is the distance between the front and rear axle, F is the distance between the CG (green) and the front axle, R is the distance between the CG and the rear axle.

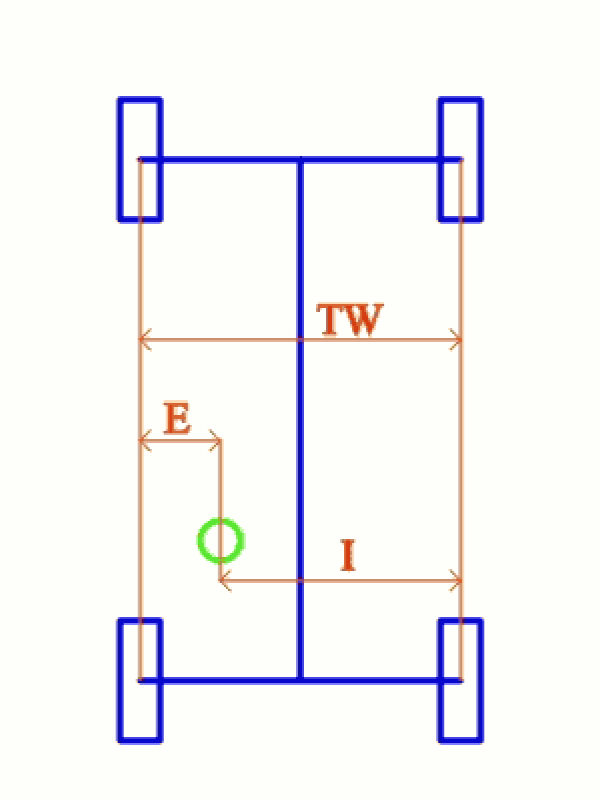
Weight on the front axle = weight of the car*(R/WB)
Weight on the rear axle = weight of the car*(F/WB)

Or, in percentages:

Front weight percentage = (R/WB)*100%
Rear weight percentage = (F/WB)*100%

Obviously, this will have its effects on handling: more weight on a tire means more grip. So if the CG is located further towards the rear, the car will have a lot of rear traction, which is nice to have if acceleration is important. If the CG is located further towards the front, the car will have a lot of steering, but it might lack rear traction, which increases the risk of spinning out.

In some cases, lateral weight distribution is a major concern, especially in so-called LTO (left turn only) cars, which race on oval tracks. It's basically the same deal:



TW is the treadwidth, the distance between the centres of the tires at the axle, E is the distance between the CG (green) and the centreline of the left side tires, I us the distance between the CG and the centreline of the right side tires. If the front and rear axles aren't equally wide, E and I have to be measured at the CG.

Weight on left side = (I/TW)*weight of the car
Weight on right side = (E/TW)*weight of the car

Or, in percentages:

Left side weight percentage = (I/TW)*100%
Right side weight percentage = (E/TW)*100%

Note that if you need to know the amount of weight on one tire, you need to multiply the weight of the car by 2 factors, one of the lateral balance, and one of the longitudinal balance, for example:

Weight on left front tire = Weight of the car*(I/TW)*(R/WB)
Weight on right front tire = Weight of the car*(E/TW)*(R/WB)
Weight on left rear tire = Weight of the car*(I/TW)*(F/WB)
Weight on right rear tire = Weight of the car*(E/TW)*(F/WB)

Note that this is only true when the car isn't tweaked; spring preload should be the same on the left and right hand side.

Again, having the CG away from the centre of the car has consequences for the car's handling: having it toward the left improves the car's ability to turn left, but it might make it very difficult to drive the car in a straight line, especially under acceleration.

The height of the CG is also very important: it determines the car's roll characteristics.

# 3. BALANCE

Balance is without a doubt one of the most important requirements for a well handling car, you might say it is the very key to having a fast, confidence-inspiring car.

It’s mainly because there are two suspension systems in a car: one in the front and one in the rear, and they are forced to work together. As you might expect, if they’re not tuned to do more or less the same thing, ’working together’ can become very difficult.

Consider the following example: a car with a perfectly symmetrical weight distribution, i.e. the same amount of weight on the four tires, and all the springs and dampers are of equal stiffness. But the rear roll centre is much lower than the front. If this car were to enter a corner, it would turn in nicely, but after that, it would understeer horribly. Let’s have a look at what actually happens. The front has a high roll centre, so the roll moment will be very small; the front end of the chassis will not want to roll very far. In the rear, it’s the opposite: the RC is very low, so the roll moment is very big; the rear end of the chassis will want to roll very far. Since the spring rates, or for that matter, wheel rates are equal at both ends, the force that tries to prevent the chassis from rolling will be the same, so the rear will want to ’outroll’ the front. For instance, the front will want to roll 2 degrees, and the rear will want to roll 10 degrees. Obviously, if the chassis is a rigid structure, this will not happen, it will roll to the average of the two roll angles: 6 degrees. So neither the front, nor the rear is where it should be. The front would have transferred the right amount of weight from the inside front to the outside front tire if the chassis would have rolled 2 degrees, but it rolled 6 degrees, so a lot more weight has been transferred onto the outside front tire than expected. In the rear, the opposite has happened: if the chassis would have rolled 10 degrees, the right amount of weight would have been transferred onto the rear outside tire, but since the chassis only rolled 6 degrees, a lot more weight has remained on the inside rear tire. This is not a very healthy situation, and it doesn’t allow the car to take a corner in a smooth, predictable, and fast manner. The excess weight on the inside rear tire, and the high amount of grip associated with it will push the car towards the outside of the corner; it will cause an understeer condition, especially under power. The excess weight, and grip, on the outside front tire will cause an unpredictable oversteer situation. So you see, the front and the rear are fighting each other, and this will only become worse when throttle or brake is applied. If more throttle is applied, more weight will be transferred to the rear, so there will be even more weight on the rear inside tire, causing an even bigger push. More brake means more weight on the outside front tire, which in normal circumstances is a good thing, but in this case there already was too much weight on it, so it will result in more oversteer. Needless to say, this is not the fastest way around the corner, and the car will require an incredible amount of driving skill. Having springs in the rear that are too soft would have caused a similar problem.

So, what does this example teach us? It teaches us that the front and the rear of the car should always be able to work together, but that’s not all; we can also use the insight it provided us to tune a car to our specific handling needs, by purposely changing the balance.

To be able to judge if your car is balanced or not, you’ll need some kind of baseline comparison. I use the following, imaginary set-up: a car with the CG right in the middle, and identical springs, dampers and roll centres front and rear. It’s pretty obvious this car is balanced, but usually, front wheel drive cars will have more weight on the front axle, and rear wheel drive cars will have more weight on the rear axle. This is easy to compensate by just increase spring stiffness and damping by the same ratio as the CG moved. For example: if the rear has twice as much weight on it than the front, use springs that are twice as stiff in the front, and use a damper rate that’s also twice as thick. If you try this, you’ll find that it’s very easy to drive, predictable and stable, and generally well suited to extreme track conditions. But you might not find it aggressive enough, or think that it’s got a little too much steering for our taste…

But there's a remedy for that; you can make the changes you like, as long as you don't disturb the balance too much. For instance, you can move the weight forward a little, but use a stiffer spring in front. This will give you more weight on the front tires, statically. So you'll get more turn-in, and probably a little more on-power steering, but you'll lose some rear traction. Or you can use an anti-roll bar in the rear, but use slightly softer rear springs. This will give you more steering in the middle part of the corner, and it will give you more forward traction. Another thing that’s being used a lot is to use a higher RC in the rear than in the front, combined with stiffer springs (and damping) up front, and softer ones in the rear. This makes for a very stable car: it will turn in sharply at first, because of the stiff springs up front, but then, it will understeer a little, because with the stiff springs and heavy damping up front, it takes some time to transfer the weight onto the outside front tire. This happens a lot faster in the rear. But eventually, when the weight is fully transferred, the car will steer very well. This set-up can be very fast: the car can be ’thrown’ into the corner, without losing a lot of speed because of the mild understeer. Then, at the apex of the turn, some braking will probably be needed, but after that the car will be very stable again, like in the entrance of the turn, which makes a high exit speed possible.

# 4. DOWNFORCE

In essence, downforce is a force that’s pushing down on the car, and therefore also on the tires. In a way, this is like ’free grip’: it doesn’t require any weight shifting, that’s also why most of the time, the distinction is made between ’mechanical grip’ and ’aero grip’. It isn’t totally free though: more downforce also means more drag, i.e. more wind resistance, so you’ll always have to find the best possible compromise between grip and aerodynamic drag.

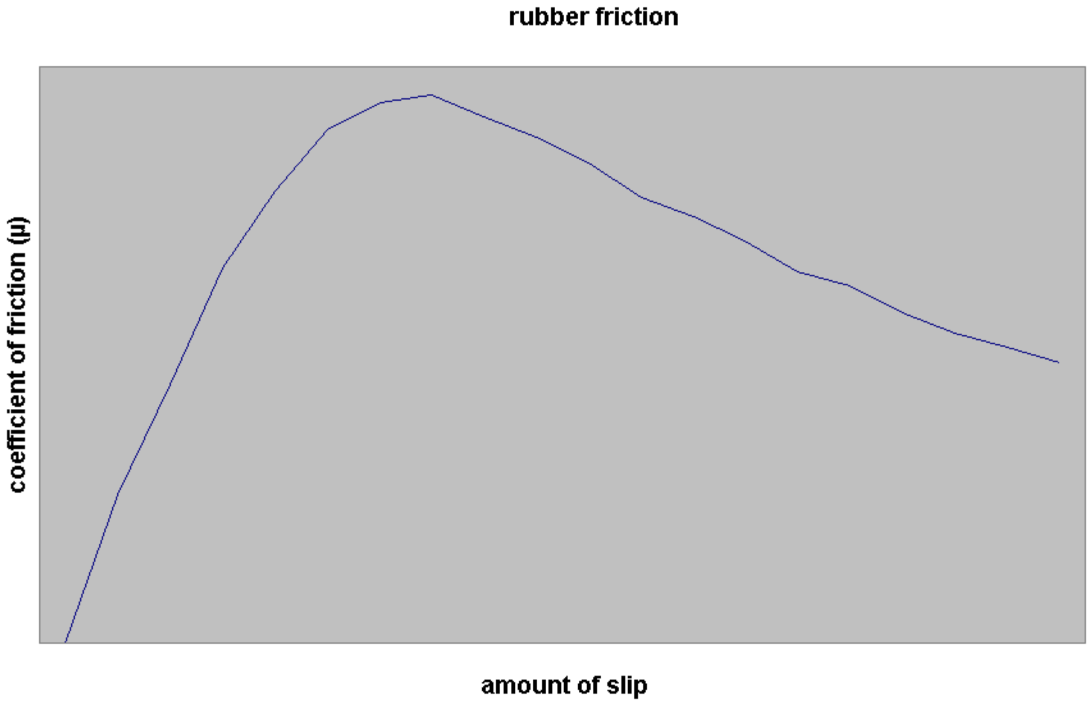
Another thing that’s very important is the fact that downforce is proportional to speed, more precisely the speed of the air relative to the car. So at low and very low speeds, downforce is negligible. Remember this when you have to set up your car for slow corners: downforce won’t have a lot of influence. At high speeds however, downforce is in most cases dominant over the mechanical settings: in high-speed corners, adjusting downforce is the only way to go.

# 5. TYRES

Tires are the most important element in the quest to get a car to handle well. They're the only link between the car and the earth. That link depends solely on the friction between the surface and the tyre's contact patch, so let's have a look at how friction works.

## 5.1. Friction

The formula for friction between two surfaces is side load = μ * weight. μ Is the coefficient of friction. For a rubber tire, μ is definitely not constant; it varies with temperature, pressure and more importantly, amount of slip. This is represented in the next graph.



On the horizontal axis is the amount of slip, from 0%(no slip, the tire just rolls along) to 100% (Either the tire is standing still and the vehicle is moving, or the vehicle is standing still, but the tire is moving). On the vertical axis is the coefficient of friction. In the left part of the graph, slip within the tire is dominant, also known as tire squirm. This happens when the tire deforms under load and the contact patch moves relative to the axle. This also causes slip angles to exist. In the right part, slip between the two surfaces is dominant; the tire starts to slide sideways a little. It is remarkable that μ reaches its maximum when there is a little slip, usually it's between 5% and 15%. That's because rubber interacts with the surface in a very special way.

In fact, the reason why the graph has such an odd shape is because it's a combination of things, there are two separate mechanisms involved: hysteresis and adhesion.

The first component, adhesion, is the phenomenon that the outermost atoms of the rubber molecules are in direct contact with the outer molecules of the surface. Rubber is a polymer, and its molecular structure resembles spaghetti of strings of atoms, the surface is most of the time crystalline, in which the atoms are more closely together. So when there is a speed difference between the two, the 'atom strings' in the rubber will be stretched. Some molecular bonds will break, and new ones will be formed. This process repeats itself as the one surface is dragged over the other. Obviously, breaking and stretching molecular bonds, and moving atoms around takes energy, and hence also a force. That is the adhesion force. It reaches its maximum when the speed difference is somewhere between 0,03 and 0,06 meters per second.

The second component, hysteresis, exists because rubber is being deformed. As the tire carcass is being distorted, in some areas the rubber gets compressed, and in other areas it gets stretched. For stretching to be possible, the atoms must move alongside each other, and as always, it's an irreversible process because of friction. The friction will make the tire heat up. Again, all this takes energy, and thus a force. That force is the hysteresis force, which is very similar to the adhesion force, only its size is determined by the internal friction in the rubber.

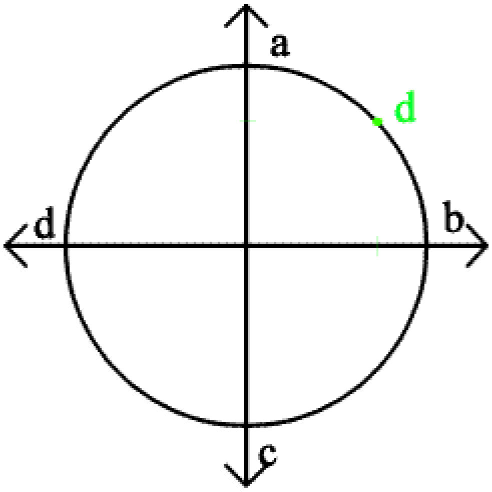
As the weight on the tire and the amount of slip vary, the proportion of the two components changes. For example, if there is more slip, the hysteresis component will be dominant over adhesion. If the rubber compound is very soft, and the temperature is high and the surface smooth, adhesion will be the dominant force.

Note that all the above is valid for very hard racing surfaces, like asphalt or really hard clay. If the surface is soft, it's the deformation of the surface that causes the friction force to exist: the spikes on the tires dig into the surface, and make grooves into it. In that case, the graph doesn't have a section that's curved down; μ always increases as the weight on the tire and the amount of slip increases. It's a totally different mechanism. That's also the reason why when an on-road car takes a turn, and transfers weight onto the outside tires, its cornering power decreases, while when an off-road car does the same thing, its cornering power increases. So it makes sense for on-road cars to have high roll stiffness (think anti-roll bars), and for off-road cars to have a very low one.

## 5.2. The traction circle

Now that we know how friction works, and how it is usually maximal when there is a little slip, let's find out how it influences the car's handling.

Unless the tyre's thread isn't symmetrical, friction is the same in all directions, and it also has a maximum value, which is also the same in all directions. The traction circle can represent this.



The vertical component of the graph represents acceleration and deceleration, and the horizontal component represents turning left and right. The maximum amount of grip is represented by the edge of the circle, and the area of the circle represents the amount of grip of the tire on the road.

Naturally, the fastest way around a track is to use your tires to their very limit. So, to brake as fast as possible, you will need to take the tires to point C on the graph. If you brake too hard, and you exceed point c on the graph, you will skid, and your braking distance will increase. You might even lose control. The same thing goes for acceleration: if you exceed point a, you will experience a lot of wheelspin, and you'll accelerate slower. It's also possible to exceed the grip limits when cornering (points D and B), and spin out.

But the hardest parts to judge aren't the axis lines; it's the parts in between. Point D for example represents a situation where the car is turning right and accelerating. Note that D is on the edge of the circle, yet the car isn't accelerating or turning at its maximum speed, it's somewhere in between. Let's say you are accelerating as fast as possible (point A), and you steer a little towards the left. On the graph, this means you're at a point left of a, which is outside the circle, so the tires will break loose, and the car won't turn (front wheel drive) or spin out (Rwd). Another interesting fact is that in order to get the most cornering power, there shouldn't be any power applied to the wheels. (Points B and D) And conversely, in order to get the fastest possible acceleration or braking, no steering should be applied.

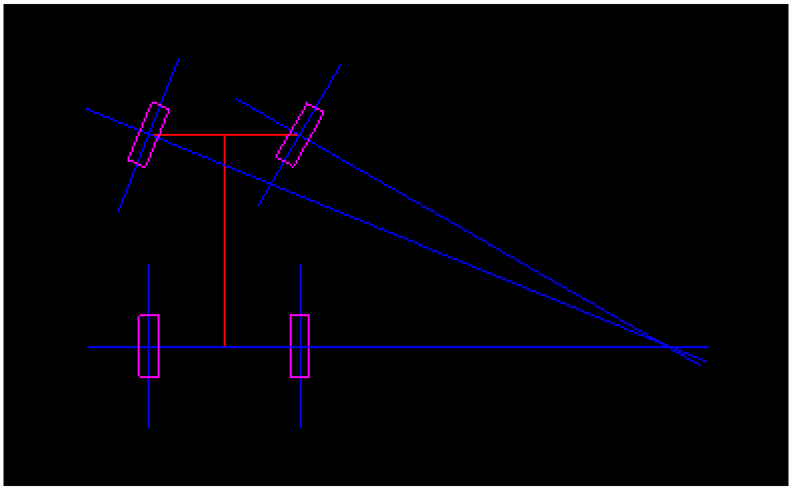
Keep in mind that the radius of the traction circle represents the maximum adhesion force, and this is proportional (well, kind of, as explained in the previous paragraph) to the vertical load on the tire. So, in brief: the size of the circle increases as more vertical pressure is exerted on the tire, and it decreases if there's less vertical pressure on it. The circle doesn't even exist when there's *no* pressure on the tire. It makes sense, because a tire that's hanging in the air can't resist any lateral force.

## 5.3. Slip angles

You might have wondered what exactly happens when you go beyond the traction circle, and how your car will react. Slip angles provide a clear way of describing this.

A slip angle is the angle between where the tire is pointing and where it actually going. Each tire has its own slip angle.

A tire that's not slipping has a slip angle of zero degrees.

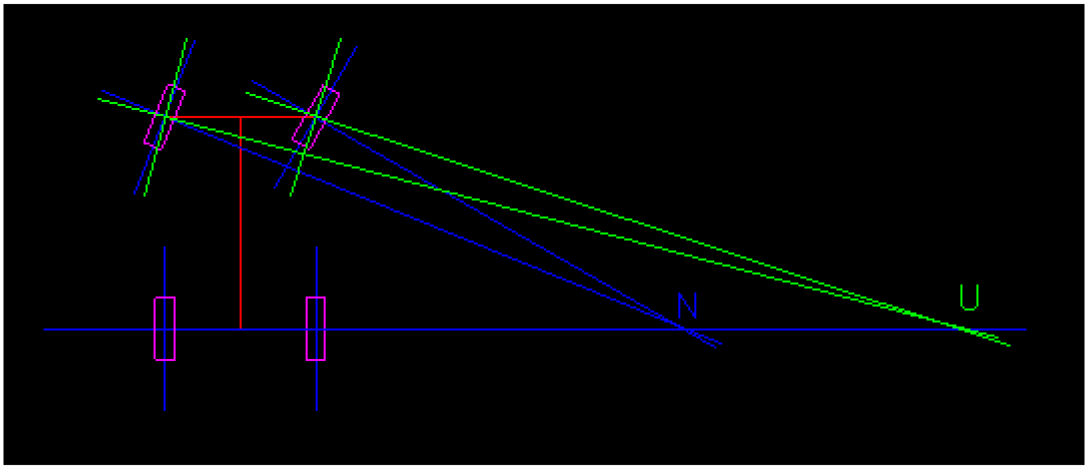


This next drawing represents a car taking a turn at low speed. All four slip angles are zero.

Assuming the car has the correct Ackermann effect and no rear toe-in, the car can turn with none of the tires slipping. Note that the imaginary (well they're not so imaginary when I draw them out for you) lines through the four axles intersect at **one point.** That's the point the car is turning around. Sort of like the apex of the corner the car is taking.

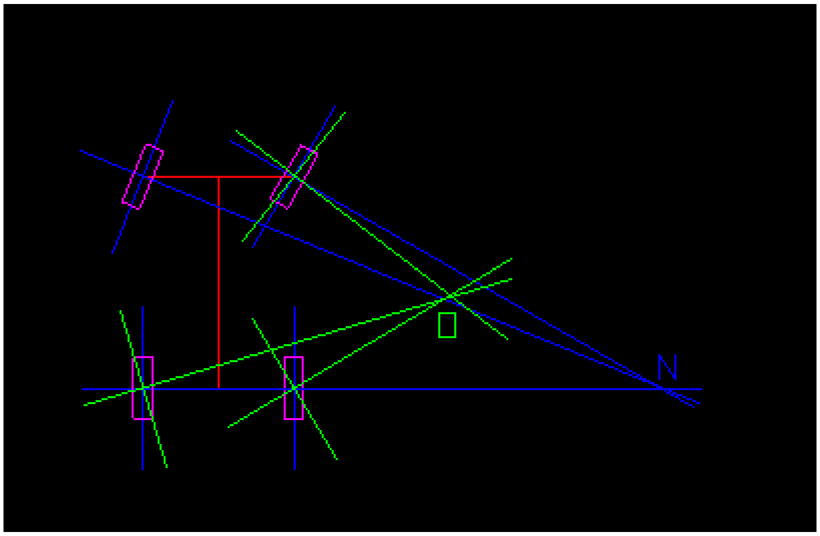
This is a typical situation when cornering speed is low, and all four tires have more or less the same weight on them.

But...unfortunately, things aren't always like you want them to be. One common condition is **understeer**. This happens when the front tires don't have enough weight on them, and they start to slip, hence creating a slip angle.



The slip angle of the front tires is the angle between the blue lines and the green lines. The car is not turning around the point you'd expect, or want it to turn. (where the blue lines intersect, point N) Instead, it's turning around the intersection point of the green lines (point U), which makes for a larger turning radius than expected. This is understeer: when the turning radius is bigger than you'd like it to be.

The opposite can also happen: the rear tires can have insufficient weight on them, and start to slip. This usually leads to a condition called **oversteer**, where the turning radius is smaller than you'd expect it to be.

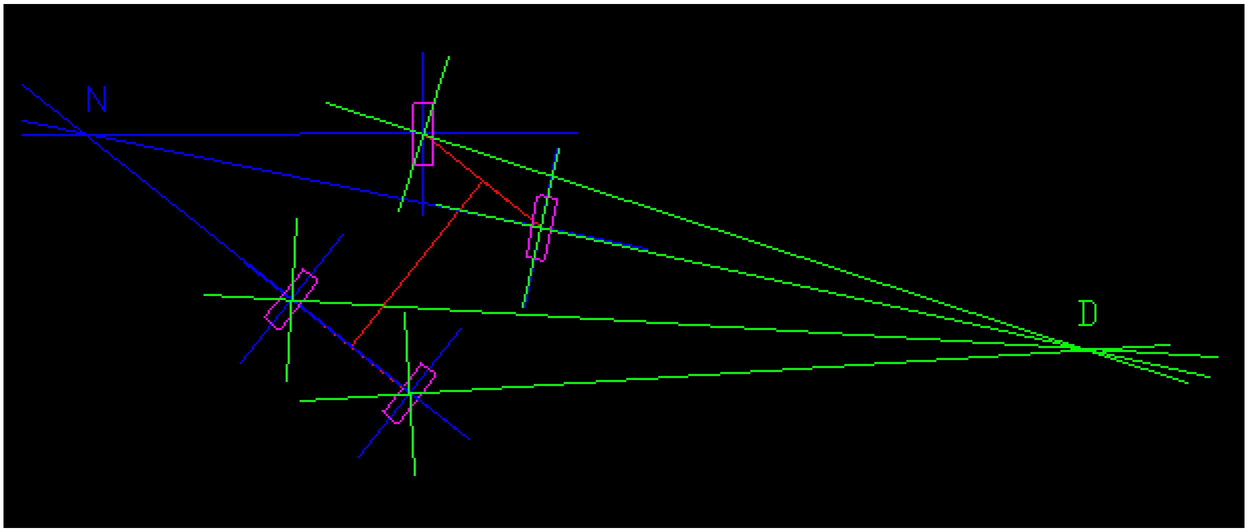


Here, the rear tires have started to slip, creating slip angles at the rear of the car. The inside front tire has also started to slip. This is because the car can't be turning around two separate points at the same time. In this case, the car is turning around point O, (whereas the driver would have expected it to be turning around point N.) When a car is cornering, the lines representing the slip angles always intersect at the point the car is rotating around. If they don't, the tire with the least amount of weight on it (in this case the inside front) will develop a slip angle.

Notice that the point which the car is rotating around (O) is now much closer to the centre of the car, and more towards the front. The car will turn very sharply, much sharper and earlier than expected.

Plain over- and understeer are very common conditions, but in reality, all sorts of wacky things can happen.

For example: you can power slide around the corner.



Although the front wheels are steered to the left, the car is turning to the right. (countersteering) The rear tires are sliding at an extreme angle.

No need to say this requires some serious driving skill.

# 6. GEARING

This is probably the most straightforward issue of all. In most cases, the best gear ratio is the one that allows your car to accelerate as fast as possible, without over-revving your motor on the straight. So finding the right gear ratio is quite simple in most cases: just make sure the motor reaches maximum revs towards the end of the longest straight.

However, in some cases it can be beneficial for your lap times to over- or undergear your car: a slightly undergeared car will accelerate faster, so the track is full of short straights where acceleration is very important, you might want to consider a smaller ratio. Overgearing is frequently used to prevent wheelspin under acceleration, mostly on low-traction tracks. It can make the car somewhat easier to drive. It's only advisable on tracks where wheelspin is a problem.

A gear ratio indicates the number of revolutions of the motor has to do for the wheel to complete one full revolution. For example: a ratio of 9.0 means that when the motor has done 9 complete rotations, the wheel will have done just one, if the motor has done 18, the wheel will have done 2...

Here's the tricky part: a higher number means a smaller ratio, and conversely a smaller number means a higher ratio. So 9.0 is a taller or higher ratio than 10.0. Think about it: if the motor has to do fewer rotations for the wheel to do one (smaller number), the car will go faster for the same rpm, which means a taller ratio.

# 7. MAKING ADJUSTMENTS

The purpose of making adjustments is to make the car go faster around the track, or to make it more controllable, or often both. A car that's easier to drive often causes lower, more consistent lap times, and more importantly, it will inspire the driver more confidence, which comes in handy when the going gets rough.

The first and most important step towards making an adjustment is determining the cause of the handling deficiency you wish to cure. Experienced drivers/mechanics or people with a lot of insight in vehicle dynamics will just know or feel this. In order to know what to change, you need to know what each element does, and does not do. For instance: changing the front toe angle does not change the balance of the car, it just changes the way the car reacts going into corners. From all the previous chapters, it should be clear, but in reality, it can be difficult to judge the difference between what the car is doing and what you'd like it to do.

Here are a few examples.

When you're racing on a big, flowing track that has a lot of shallow, rhythmic bumps in it, don't be tempted to use both a soft setting for springs and damping and a very low roll centre: the chassis will roll from side to side in every small bump, resulting in a very unstable, unpredictable car with very little traction. In this case, *stiffening* both the damping and the springs will *increase* traction, but it won't be the best solution, that would be raising the RC, and making sure it stays high when the chassis rolls. Note that when the bumps are sort of rhythmic, soft settings for dampers and springs will make the chassis 'resonate' to the bumps, which causes a weird form of instability. In that case, damping and maybe springs that are a little harder would be better; it will make the car skip over the bumps instead of plunging into every one of them very deeply. And it's not just side-to-side movement that can be excessive on a bumpy track: if your car has a lot of negative suspension travel, its chassis can suffer from excessive pitch: it will kind of rock back and forth. The answer is simple: reduce the downtravel. Even though this will make the car bottom out on large jumps and bumps a little more, it will be a lot more stable in bumpy sections, especially sections where the car is accelerating or braking.